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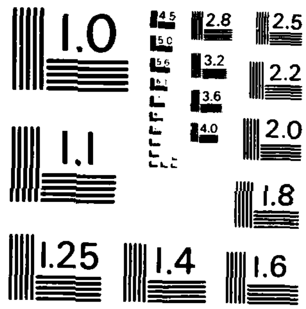

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TOROIDAL SELF-FIELD CORRECTIONS TO THE LINEAR DISPERSION RELATION FOR THE NEGATIVE MASS INSTABILITY IN A MODIFIED BETATRON

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

When normal man goes to high altitude ventilation increases immediately but there are further increases as acclimatization proceeds. The early days of exposure are important because breathing at this time may be one determinant of well-being. Breathing after acclimation has

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occurred is important because it may be one determinant of performance. We considered that shortly after arrival at high altitude increased breathing was stimulated by hypoxia, but the increase was limited by hypocapnic alkalosis and by (possibly) hypoxic depression of central mechanisms controlling ventilation. We considered that by comparing proper ventilatory measurements made at low altitude with actual values at high altitude we might gain insight into controlling mechanisms and we might also develop tests of predictive value. The low altitude tests included an acute hypoxic stimulus where CO_2 was not allowed to change as hypoxia developed. This isocapnic hypoxic response was taken as a pure measure of the ventilatory response to hypoxia. A second low altitude test, designed to be analogous to the actual high altitude exposure, was acute hypoxic exposure where CO_2 was allowed to change (poikilocapnia) because no CO_2 was added to the inspired air. In comparing the ventilatory responses to these two low altitude tests for 12 male volunteers we found as expected that for the group as a whole ventilation was less during poikilocapnic hypoxia than during isocapnic hypoxia. The unexpected finding was that in 4 subjects the two responses were not different and that these subjects had particularly low ventilatory sensitivity to CO_2.

When the 12 subjects were taken from low altitude (1600M in Denver, CO) to high altitude (4300M on Pike's Peak) they underwent acclimatization over 5 days. The surprising finding was that on day 4 and day 5 their ventilations were predicted by the acute isocapnic hypoxic response at low altitude. It was as though, after acclimatization, the relatively pure response to acute hypoxia was a major determinant of ventilation. On arrival at high altitude (Pike's Peak day 1) the ventilation showed only a small increase above the Denver value, as though the response to hypoxia were inhibited. The inhibition could be accounted for only in part by the hypocapnic alkalosis. To account for the remainder we recalled the subjects some months later and subjected them to more prolonged, i.e. 30 minutes, poikilocapnic hypoxia. Ventilation rose and then fell documenting the presence of hypoxic depression. The level achieved was that observed on Pike's Peak day 1. The two factors inhibiting ventilation on arrival then appeared to be both hypoxic depression and hypocapnic alkalosis.

Total ventilation, however, was not the most sensitive measure of acclimatization because we found it was influenced by metabolic increases at rest and dead space increases during exercise. A more sensitive measure and one that provided useful inter-individual comparisons involved the use of an SaO_2-PCO_2 stimulus response curve, similar to that proposed by Rahn and Otis. Examination of these curves in relation to high altitude values suggested that it was hypoxic depression at high altitude that was responsible for the poor ventilatory response and the development of syptoms in some individuals at high altitude.

APS PLASMA PHYSICS MEETING
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TOROIDAL SELF - FIELD CORRECTIONS TO THE LINEAR DISPERSION RELATION FOR THE NEGATIVE MASS INSTABILITY IN A MODIFIED BETATRON

B. B. GODFREY, T. P. HUGHES, M. M. CAMPBELL
MISSION RESEARCH CORPORATION, ALBUQUERQUE

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ABSTRACT

TOROIDAL SELF-FIELD CORRECTIONS TO THE LINEAR DISPERSION RELATION FOR THE NEGATIVE MASS INSTABILITY IN A MODIFIED BETATRON.

*--B. B. GODFREY, T. P. HUGHES, AND M. M. CAMPBELL, MISSION RESEARCH CORPORATION, ALBUQUERQUE, NM 87106. --NEGATIVE MASS INSTABILITY GROWTH RATES DETERMINED FROM THREE-DIMENSIONAL PIC CODE SIMULATIONS OF HIGH CURRENT MODIFIED BETATRONS DO NOT AGREE PARTICULARLY WELL WITH AVAILABLE LINEAR THEORY, AS NOTED IN A COMPANION PAPER.[1] PUBLISHED LINEAR ANALYSES OF THE NEGATIVE MASS INSTABILITY TREAT PARTICLE DYNAMICS IN TOROIDAL GEOMETRY BUT THE ELECTROMAGNETIC FIELDS IN CYLINDRICAL GEOMETRY. WE HAVE, THEREFORE, DEVELOPED A NEW MODEL EMPLOYING TOROIDAL FIELDS; IT IS VALID FOR ARBITRARY TOROIDAL MODE NUMBERS AND A VARIETY OF ACCELERATOR CAVITY MINOR CROSS SECTIONS. THE BEAM MINOR RADIUS IS ASSUMED SMALL COMPARED TO THAT OF THE CAVITY. DERIVATION OF THE DISPERSION RELATION AND NUMERICAL SOLUTIONS OF IT WILL BE PRESENTED.

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*WORK SUPPORTED BY THE OFFICE OF NAVAL RESEARCH.

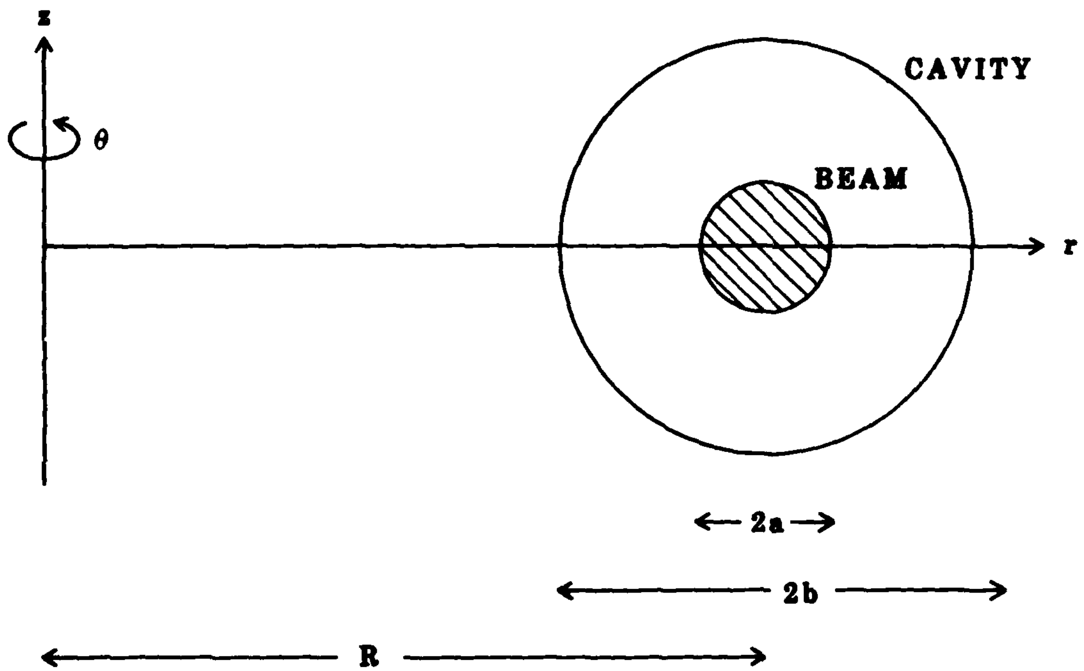
1. T. P. HUGHES, M. M. CAMPBELL, AND B. B. GODFREY, "SIMULATION AND THEORY OF THE NEGATIVE MASS INSTABILITY IN A MODIFIED BETATRON," THIS CONFERENCE.

INCLUDING TOROIDAL FIELD CORRECTIONS IN MODIFIED BETATRON DISPERSION RELATION IMPORTANT FOR ACCURATE ESTIMATE OF NEGATIVE MASS INSTABILITY GROWTH.

- EXISTING MODELS INCLUDE TOROIDAL FIELD CORRECTIONS INCOMPLETELY OR NOT AT ALL
- COMPUTER SIMULATION RESULTS OFTEN DIFFER SIGNIFICANTLY FROM DISPERSION RELATION PREDICTIONS
- LARGE TOROIDAL FIELD COUPLING IDENTIFIED — RADIAL ELECTRIC SELF-FIELDS DRIVE BEAM AZIMUTHAL OSCILLATIONS, AND CONVERSELY

PRESENT ANALYSIS ADDS TOROIDAL FIELD EFFECTS TO LINEAR DISPERSION RELATION IN LONG WAVELENGTH LIMIT.

COMPUTATIONS PERFORMED IN CYLINDRICAL GEOMETRY, APPLY TO TOROIDALLY SYMMETRIC BEAM AND CAVITY WITH CIRCULAR MINOR CROSS SECTIONS.



BEAM CENTROID EQUATIONS DRIVEN BY EQUILIBRIUM, PERTURBED FIELDS

$$\gamma \delta \ddot{z} = \delta E_z - V_\theta \delta B_r + B_\theta \delta \dot{r} + \left(\frac{\partial E_z}{\partial z} - V_\theta \frac{\partial B_r}{\partial z} \right) \delta z$$

$$\gamma \delta \ddot{r} = \delta E_r + V_\theta \delta B_z - B_\theta \delta \dot{z} + \left(\frac{\partial E_r}{\partial r} + V_\theta \frac{\partial B_z}{\partial r} - \frac{\gamma V_\theta^2}{R^2} \right) \delta r$$

$$+ \left[(\gamma^2 + 1) \frac{\gamma V_\theta}{R^2} + B_z \right] \delta V_\theta$$

$$\gamma^3 \delta \dot{V}_\theta = \delta E_\theta + \frac{E_r}{V_\theta} \delta r$$

EQUILIBRIUM BEAM VELOCITY SET BY RADIAL FORCE BALANCE.

$$E_r + V_\theta B_z + \gamma V_\theta^2 / R = 0$$

PERTURBED POTENTIAL EQUATIONS TAKE SIMPLE FORMS IN LONG WAVELENGTH, LOW FREQUENCY LIMIT

$$\left(1/r\ \partial/\partial r\ \ r\ \partial/\partial r + \partial^2/\partial z^2\right)\ \delta\phi = -\ \delta\rho$$

$$\left(\partial/\partial r\ \ 1/r\ \partial/\partial r\ \ r + \partial^2/\partial z^2\right)\ \delta A = -\left(\rho\ \delta V_\theta + V_\theta\ \delta\rho\right)$$

- PERTURBED DENSITY GIVEN BY CONTINUITY EQUATION

$$\delta\rho + \partial/\partial\theta\ \ \rho\delta\theta + 1/r\ \ \partial/\partial r\ \ r\ \ \rho\delta r + \partial/\partial z\ \rho\ \delta z\ = 0$$

BEAM AND FIELD EQUATIONS — FOURIER TRANSFORMED IN TIME AND ANGLE — FORM COMPACT, SELF-ADJOINT SYSTEM

$$
\begin{pmatrix}
\alpha_z & -i\Omega B_\theta & 0 & -\partial/\partial z & V_\theta\, \partial/\partial z \\
i\Omega B_\theta & \alpha_r & -i\Omega\beta & -\partial/\partial r & V_\theta\; 1/r\; \partial/\partial r\; r \\
0 & i\Omega\beta & \Omega^2\gamma^3 & -i\,\ell/r & i\omega \\
\partial/\partial z\; \rho & 1/r\; \partial/\partial r\; r\rho & i\,\ell/r\,\rho & -(1/r\; \partial/\partial r\; r \cdot \partial/\partial r + \partial^2/\partial z^2) & 0 \\
-V_\theta\; \partial/\partial z\; \rho & -V_\theta\; \partial/\partial r\; \rho & -i\omega\rho & 0 & (\partial/\partial r\; 1/r \cdot \partial/\partial r\; r + \partial^2/\partial z^2)
\end{pmatrix}
\begin{pmatrix}
\delta z \\ \delta r \\ r\,\delta\theta \\ \delta\phi \\ \delta A
\end{pmatrix}
= 0
$$

EQUILIBRIUM QUANTITIES, OTHER TERMS IN MATRIX:

$$E_r = \rho/2 \ (r-R) + (\rho a^2/16R)(a^2/b^2 + 4 \ ln \ b/a)$$

$$B_r = B_z^o \ n \ z/R \qquad B_\theta = B_\theta^o$$

$$B_z = -V_\theta \ \rho/2 \ (r-R) + V(\rho a^2/16R)(-a^2/b^2 + 4 + 4 \ ln \ b/a)$$
$$+ B_z^o \ (1-n(r-R/R))$$

$$\alpha_z \equiv \partial E_z/\partial z - V_\theta \ \partial B_r/\partial z + \gamma \Omega^2$$

$$\alpha_r \equiv \partial E_r/\partial r + V_\theta \ \partial B_z/\partial r + \gamma \Omega^2 + V_\theta/R \ (\gamma^3 \ V_\theta/R + B_z)$$

$$\beta \equiv \gamma^3 \ V_\theta/R - E_r/V_\theta \qquad \Omega \equiv \omega - l/R \ V_\theta$$

TWO ORDERING SCHEMES CONSIDERED FOR SOLVING EQUATIONS

- SIMPLE ALGEBRA, REASONABLE AGREEMENT WITH SIMULATIONS
  - ω, $l/R \sim 1$
  - EQUATIONS EXPANDED TO FIRST ORDER IN R^{-1}
- DIFFICULT ALGEBRA, GREATER INTERNAL CONSISTANCY
  - ω , $l/R \sim 1/R$
  - EQUATIONS EXPANDED TO SECOND ORDER IN R^{-1}

- FIRST OPTION USED HERE, WORK ON SECOND IN PROGRESS

RESULTING DISPERSION RELATION CLEARLY EXHIBITS COUPLING BETWEEN LONGITUDINAL, TRANSVERSE POLOIDAL MODES.

$$(\Omega^2 - \omega_z^2)\ (\Omega^2 - \omega_r^2 - \chi/\epsilon) - \Omega^2\ B_\theta^2/\gamma^2 = 0$$

$$\epsilon \equiv \Omega^2 - \nu/\gamma^3\ (1/2 + 2\, ln\, b/a)\ (\ell^2/R^2 - \omega^2)$$

$$\chi \equiv \Big((\gamma V_\theta/R - E_r/\gamma^2)\Omega + (\nu/4R\gamma^2)\big[\omega V_\theta\ (3-3\ a^2/b^2 + 4\, ln\, b/a)$$
$$+ \ell/R\ (1 + a^2/b^2 + 4\, ln\, b/a)\big]\Big)^2 - \epsilon\ (\gamma V_\theta/R - E_r/\gamma^2)^2$$

$$\omega_z^2 \equiv -n\ V_\theta B_z^o/\gamma R - 2\nu/\gamma^3 b^2 \qquad \nu \equiv \rho a^2/4$$

$$\omega_r^2 \equiv -(1-n)\ V_\theta B_z^o/\gamma R\ - 2\nu/\gamma^3 b^2\ - (2E_r^s + B_z^s)/\gamma R + (E_r/\gamma^2 V_\theta)^2$$

$$E_r^s \equiv \nu/4R\ (a^2/b^2 + 4\, ln\, b/a) \qquad B_z^s \equiv \nu/4R\ (-a^2/b^2 + 4 + 4\, ln\, b/a)$$

TOROIDAL FIELD CORRECTIONS PRINCIPALLY IN COUPLING COEFFICIENT χ – FACILITATES FORMAL COMPARISON AMONG MODELS.

- P. SPRANGLE AND J. C. VOMVORIDIS, NRL REPORT 4688

$$\chi = (\gamma V_\theta / R)^2 \; (\Omega^2 - \epsilon)$$

- T. P. HUGHES AND B. B. GODFREY, AMRC REPORT 469

$$\chi = (\gamma V_\theta / R)\, \Omega \left[(\gamma V_\theta / R)\, \Omega + (\ell \gamma / R^2)\; \nu / \gamma^3 \; (1 + 2 \, \ln b/a) \right] - (\gamma V_\theta / R)^2 \; \epsilon$$

LOW CURRENT NEGATIVE MASS GROWTH RATE FOR STANDARD BETATRON ($B_\theta = 0$) EASILY RECOVERED.

- SIMPLIFIED DISPERSION RELATION

$$\omega_r^2 \, \epsilon \approx - \chi$$

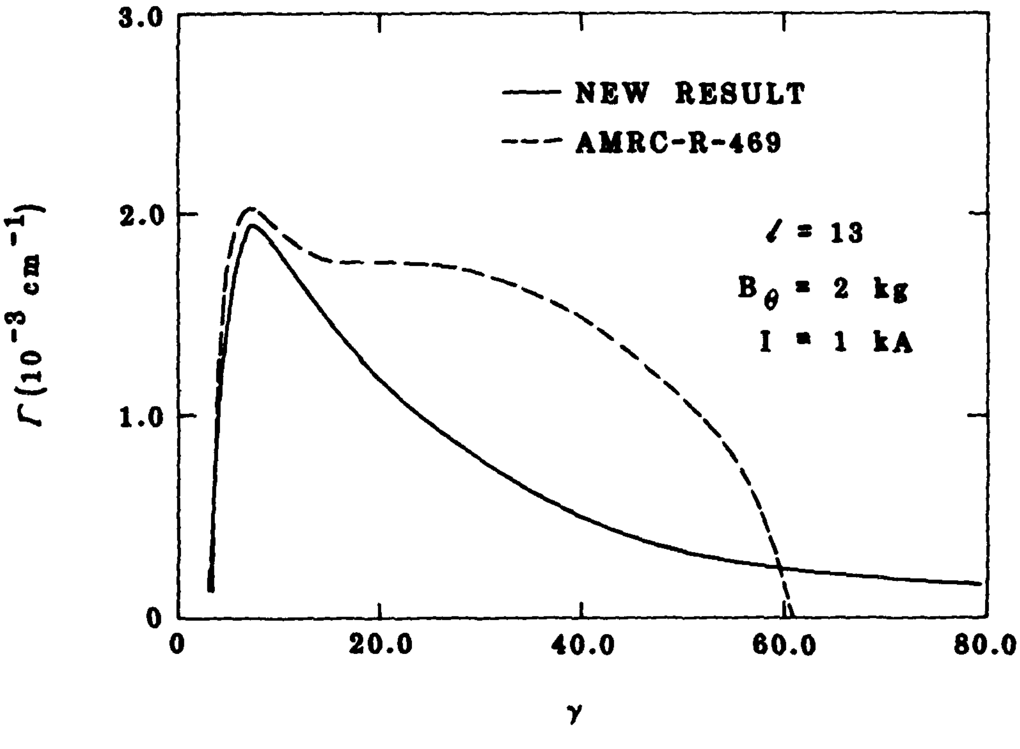
- INSTABILITY GROWTH RATE

$$\Gamma \approx \omega_r^{-1} \left[\left(V_\theta^{\,2}/R^2 - \omega_r^{\,2}/\gamma^2 \right) \; \nu/\gamma^3 \; \left(1/2 + 2 \ln b/a \right) \right]^{1/2} \ell/R$$

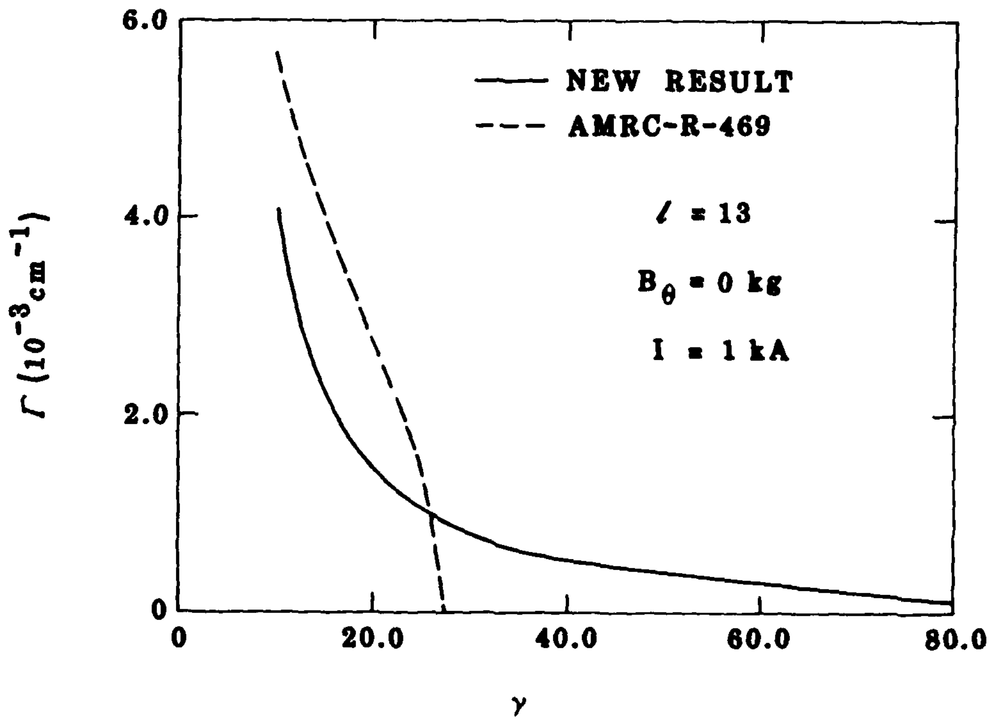
- VALID IN SMALL $\nu\gamma$ LIMIT

$$\left[\nu \gamma \; \left(1/2 + 2 \ln b/a \right) \right]^{1/2} << n/2$$

NEW DISPERSION RELATION PREDICTS REDUCED NEGATIVE MASS GROWTH FOR NRL-ONR RACETRACK INDUCTION ACCELERATOR DESIGN.



NEGATIVE MASS INSTABILITY HIGH ENERGY CUTOFF NO LONGER PREDICTED FOR MODERATE CURRENT $B_\theta = 0$ BETATRONS.



NEW LONG WAVELENGTH NEGATIVE MASS INSTABILITY DISPERSION RELATION DEVELOPED FOR MODIFIED BETATRON.

- INCLUDES TOROIDAL FIELD EFFECTS TO FIRST ORDER IN ASPECT RATIO
- YIELDS IMPROVED AGREEMENT WITH SIMULATION RESULTS (SEE ADJACIENT PAPER)
- PREDICTS REDUCED INSTABILITY GROWTH FOR RACETRACK INDUCTION ACCELERATOR

DERIVATION OF SECOND ORDER DISPERSION RELATION IN PROGRESS.

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- INVESTIGATION SUPPORTED BY OFFICE OF NAVAL RESEARCH

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